

SOURCE MODELS AND YIELD-SCALING RELATIONS FOR UNDERGROUND NUCLEAR EXPLOSIONS AT AMCHITKA ISLAND

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ABSTRACT

Source models are determined for the three underground nuclear explosions at the Amchitka test site using seismic observations in the period range 0.5 to 20.0 sec. Empirical yield-scaling relations are inferred from the source models and compared with the predictions of the Haskell, Mueller-Murphy, and finite difference numerical models. Several recent studies of high-frequency, near-field signals and teleseismic short-period *P* waves for LONGSHOT, MILROW, and CANNIKIN constrain the source functions at periods of 0.5 to 2.0 sec. Teleseismic *pS* and Rayleigh wave observations are used to constrain the source functions at longer periods. Using a modified Haskell source time function representation given by

$$\psi(t) = \psi_{\infty} \{1 - e^{-Kt} [1 + Kt + (Kt)^2/2 - B(Kt)^3]\},$$

the data are best-fit if the corner frequency parameter, *K*, scales as predicted by the Mueller-Murphy model, and if the amount of overshoot in the reduced displacement potential, which is proportional to *B*, decreases with increasing yield (depth of burial). The latter behavior is opposite to that predicted by the Mueller-Murphy model and follows from the observation that the long-period level of the explosion potential, ψ_{∞} , increases with yield, *W*, by $\psi_{\infty} \propto W^{0.90}$, or with yield and depth by $\psi_{\infty} \propto W/h^{1/3}$. This long-period and overshoot scaling is consistent with that found for some numerical models, and allowing for the depth dependence of the Rayleigh wave excitation, results in the observed *M_s* versus log(*W*) slope of ~1. The decrease in overshoot with increasing depth of burial may be the result of the increase in shear strength with increasing overburden pressure. If yield or depth dependence of the source potential overshoot proves to be a general phenomenon, a possibility supported by a preliminary investigation of Pahute Mesa observations, accurate yield estimation will require broadband seismic data. The source function representation adopted is shown to provide an excellent fit to the rise time of very near-in velocity recordings to the rise time with frequencies of 10 Hz and higher.

INTRODUCTION

The development of accurate source models and yield-scaling relations for underground nuclear explosions has been a field of intensive research for several decades. Several approaches to this problem have been taken, including: (1) direct determination of the elastic reduced displacement potential (RDP) from free-field observations (Werth and Herbst, 1963; Patterson, 1966; Perret, 1972b); (2) development of spectral scaling laws from empirical and theoretical constraints (Mueller and Murphy, 1971; Murphy, 1977); (3) fitting parameterized equivalent elastic source functions to various seismic observations (Toksöz *et al.*, 1964; Haskell, 1967; von Seggern and Blandford, 1972; Helmberger and Harkrider, 1972; Aki *et al.*, 1974; Helmberger and Hadley, 1981; Burdick *et al.*, 1982); and (4) first-principle theoretical calculations for shock wave propagation (e.g., Rodean, 1971; Cherry *et al.*, 1975).

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Rodean (1980) has reviewed the results of these different approaches and points out the fact that there is no general consensus on the detailed behavior of the explosion source time function at long periods, at high frequencies, or in the intermediate band where overshoot may occur.

In order to attain accurate yield estimation for seismic signals, it is necessary to understand the source function dependence on yield, depth of burial, and emplacement medium. This is true for purely empirical techniques such as using m_b or M_s to estimate yield, as well as for modeling procedures which utilize complete waveform information and require explicit source representations. The complex physics associated with underground explosions are not fully understood, and to a large degree it is still necessary to rely on empirical constraints to determine the appropriate source behavior. Of particular importance is establishing the relative scaling of the source spectrum at surface wave periods (~ 20 sec) and body wave periods (< 2 sec). This is basic to understanding the $m_b:M_s$ discriminant (von Seggern and Lambert, 1970), and the nature of overshoot of the source spectrum.

Since overshoot occurs near the source spectrum corner frequency, it most directly affects the amplitude of short-period P waves. While the emplacement medium dependence of overshoot has long been recognized (Werth and Herbst, 1963), the yield and depth dependence of overshoot have not been extensively addressed, nor has overshoot been convincingly demonstrated for large yield events. Haskell (1967) argued that overshoot should be independent of yield for a given medium, but he made no attempt to determine depth dependence of any of the parameters in his model. Mueller and Murphy (1971) demonstrated that depth dependence is important for the source corner frequency, and adopted empirical constraints on explosion cavities which result in the long-period spectral level, ψ_z , scaling with yield W , as $\psi_z \propto W^{0.76}$. Their results predict a slight increase in overshoot with yield (Murphy, 1977). Numerical calculations, which account for changing material properties and overburden pressure with depth, predict either a slight increase or a decrease in overshoot with increasing source depth (Cherry *et al.*, 1975; Rodean, 1980), and $\psi_\infty \propto W^{0.89}$ (Bache, 1982).

Establishing the correct source behavior among the variety of proposed models requires broadband data, which has only been available in a few instances. Most near-field recordings only provide information about the source at periods less than 2.0 sec, so it is necessary to include long-period teleseismic observations to extend the seismic bandwidth. This requires a reliable linking of near-field and teleseismic data, which has only been obtained in a few studies (Helmberger and Hadley, 1981; Burdick *et al.*, 1984), and those efforts have concentrated on obtaining effective source models appropriate only for short-period (< 2 sec) energy.

In this paper, we investigate the yield-scaling behavior of equivalent elastic source functions for the three underground explosions at the Amchitka test site; LONG-SHOT, MILROW, and CANNIKIN. The source models for these events have been extensively studied (von Seggern and Blandford, 1972; Hasegawa, 1973; King *et al.*, 1974; Burdick *et al.*, 1984; Lay *et al.*, 1984a); however, the complete implications of the source spectrum scaling have not been discussed since most studies have concentrated on narrow-band, high-frequency data. Coupling the results of recent near-field strong motion (Burdick *et al.*, 1984) and teleseismic short-period body wave (Lay *et al.*, 1984a) studies with an investigation of long-period body and surface wave signals provides the bandwidth needed to determine the broadband yield-scaling relations.

SEISMIC OBSERVATIONS OF THE AMCHITKA EXPLOSIONS

The three nuclear explosions on Amchitka Island span a large range in burial depth and yield (Table 1). A wide variety of instruments recorded these events, including borehole and close-in (<10 km) surface stations (Perret, 1972a), as well

TABLE 1
SOURCE PARAMETERS OF THE AMCHITKA TESTS

Event	Date	Latitude (°N)	Longitude (°E)	<i>h</i> (km)	Yield (kt)
LONGSHOT	29 October 1965	51.44	179.18	0.701	80
MILROW	2 October 1969	51.42	179.18	1.219	~1000
CANNIKIN	6 November 1971	51.47	179.11	1.791	<5000

TABLE 2
AMPLITUDE MEASUREMENTS FOR THE AMCHITKA TESTS

Event	<i>m</i> _b	<i>M</i> _S	Reference	
LONGSHOT	6.1 (56)	3.9 (56) (<i>M</i> _{SG})	Liebermann <i>et al.</i> (1966)	
	6.03* (32)	3.96 (18)	Marshall <i>et al.</i> (1979)	
	6.1 (32)		USCGS	
	5.8 (50)		ISC	
	5.85	4.06	Lambert <i>et al.</i> (1969)	
MILROW	6.47 (60)	4.94 (70) (<i>M</i> _{SG})	Liebermann and Basham (1971)	
	6.52* (38)	5.05 (21)	Marshall <i>et al.</i> (1979)	
	6.4 (65)		ISC	
CANNIKIN	7.02 (47)	5.74 (56) (5.56 <i>M</i> _{SG})	Willis <i>et al.</i> (1972)	
	6.89* (34)	5.69 (45)	Marshall <i>et al.</i> (1979)	
	6.8 (43)	5.7 (7)	USCGS	
	6.6 (69)		ISC	

Event	Measurement	Value	Reference
LONGSHOT	Short-period <i>P</i> “ <i>b</i> ” amplitude	226 mμ (44)	Lay <i>et al.</i> (1984a)
MILROW	Short-period <i>P</i> “ <i>b</i> ” amplitude	791 mμ (44)	Lay <i>et al.</i> (1984a)
CANNIKIN	Short-period <i>P</i> “ <i>b</i> ” amplitude	1814 mμ (38)	Lay <i>et al.</i> (1984a)
CANNIKIN/MILROW	<i>SP P</i> “ <i>b</i> ” ratio	2.74 (16)	Lay <i>et al.</i> (1984a)
MILROW/LONGSHOT	<i>SP P</i> “ <i>b</i> ” ratio	5.53 (16)	Lay <i>et al.</i> (1984a)
CANNIKIN/MILROW	<i>SP P</i> “ <i>a</i> ” ratio	4.93 (7)	von Seggern and Blandford (1972)
MILROW/LONGSHOT	<i>SP P</i> “ <i>a</i> ” ratio	6.68 (7)	von Seggern and Blandford (1972)
MILROW	Long-period <i>P</i> (1st peak)	1137.3 mμ (28)	Burdick <i>et al.</i> (1982)
CANNIKIN	Long-period <i>P</i> (1st peak)	3587.9 mμ (58)	Burdick <i>et al.</i> (1982)
CANNIKIN	Long-period <i>SV</i> amplitude	2083 mμ (21)	Burdick <i>et al.</i> (1982)
CANNIKIN/MILROW	<i>LP SV</i> ratio	7.08 (4)	Blandford and Clark (1974)
CANNIKIN/MILROW	<i>LP SV</i> ratio	4.05 (8)	This paper—Table 3
MILROW/LONGSHOT	Rayleigh wave ratio	11.5 (9)	von Seggern (1973)

* *m*₂.

as strong motion instruments in the range 7 to 12 km from MILROW and 10 to 20 km from CANNIKIN (see Burdick *et al.*, 1984). In addition, special studies were conducted to determine teleseismic *m*_b and *M*_S values for all three events, with the results summarized in Table 2. Several additional studies have reported average

amplitudes and amplitude ratios for short-period P waves, long-period P and pS waves, and Rayleigh waves for the three events, many of which are included in Table 2.

The amplitude measurements in Table 2 clearly indicate that short-period yield-scaling differs from long-period scaling for the Amchitka events. The short-period measurements include both m_b and alternate amplitude measurements of teleseismic short-period P waves, as well as the amplitude measurements of long-period P waves, which are relatively high-frequency signals (2- to 3-sec period) due to the pP interference for these explosions. The long-period measurements in Table 2 are the M_s and pS observations. On average, the short-period values indicate amplitude ratios of CANNIKIN/MILROW (C/M) ≈ 2.9 and MILROW/LONGSHOT (M/L) ≈ 4.1 . These ratios are appropriate for the period range of 1.0 to 2.0 sec. The average amplitude ratios obtained from surface waves are C/M ≈ 4.3 and M/L ≈ 11.5 . The long-period pS ratios, for which eight new measurements are listed in Table 3, give a ratio of C/M ≈ 5.0 using 12 observations. Blandford and Clark (1974) reported somewhat larger SV ratios than listed in Table 3, but there is no azimuthal pattern in these measurements that suggests that this is due to source complexity. These

TABLE 3
SV AMPLITUDE RATIOS

Station	Long-Period SV Ratio CANNIKIN/MILROW
COL	4.0
DUG	5.1
COR	4.2
MAT	3.5
QUE	3.9
INK	3.9
RES	3.9
YKC	3.9

ratios show that the long-period amplitudes vary roughly in accordance with the yield ratios of C/M ≈ 5.0 and M/L ≈ 12.5 . This is basically a reiteration of the common observation that M_s :log yield-scaling has a slope of 1.1 ± 0.1 , with the Amchitka data having a slope of ~ 1 (Basham and Horner, 1973; Springer and Hannon, 1973; Bache *et al.*, 1977; Marshall *et al.*, 1979; Bache, 1982). The similarity of the Rayleigh wave and long-period pS amplitude ratios for the larger two events is particularly important. These signals have very different propagation effects and are both sensitive to the source strength in the period range 15 to 25 sec. The pS arrival is free of the interference which produces the high-frequency long-period P signals, and ideally can be considered to be a single ray from the source.

The long-period amplitude ratios are, of course, vulnerable to contamination by nonisotropic radiation. Long-period pS signals are particularly sensitive to tectonic release (Burdick and Helmburger, 1979; Wallace *et al.*, 1983). Fortunately, several lines of evidence indicate relatively minor tectonic release for all three Amchitka tests. The evidence for this includes the low F factors found from long-period Love/Rayleigh wave ratios (Toksöz and Kehler, 1972); the moderate aftershock activity for each Amchitka event compared with NTS tests (Engdahl, 1972); the relatively small tangential component strong motion records at distances of 10 to 20 km from MILROW and CANNIKIN (Burdick *et al.*, 1982, 1984); and the low average long-period SH/SV ratio of ~ 0.33 observed for CANNIKIN at WWSSN stations (Bur-

dick *et al.*, 1984). Figure 1 shows long-period *S*-wave observations, obtained by stacking, at LASA for MILROW and CANNIKIN (Blandford and Clark, 1974). Note the coherence of the *pSV* signals and the large amplitude ratio of *C/M* ~ 7 . In both cases, the *SH* amplitudes are significantly reduced relative to the *SV* arrival, particularly for CANNIKIN. In addition, the azimuthal variation of M_s values for MILROW (Liebermann and Basham, 1971) is similar to that for CANNIKIN (Willis *et al.*, 1972), indicating that even if tectonic release is present, it is comparable in relative size and orientation between the events. Thus, we will proceed under the assumption that the long-period amplitude ratios, which are based on large numbers of observations, are free of bias due to tectonic release.

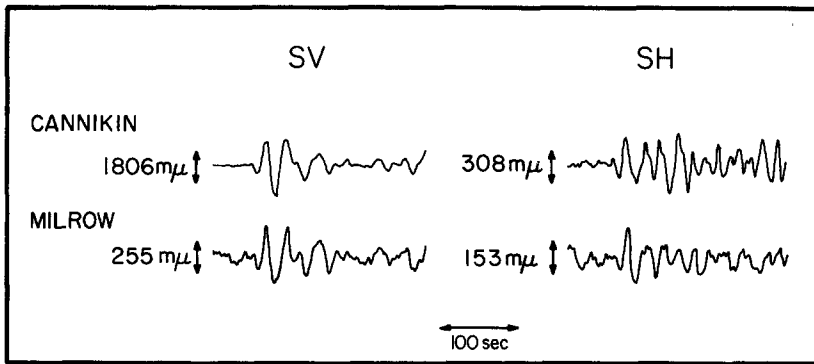


FIG. 1. Comparison of long-period *SV* (radial) and *SH* waves obtained by beam-forming at LASA for CANNIKIN and MILROW (from Blandford and Clark, 1974).

SOURCE MODELS FOR THE AMCHITKA EVENTS

Most parameterized models for the source time functions of the three Amchitka explosions have been presented in terms of the Haskell (1967) reduced displacement potential (or variations thereof) given by

$$\psi(t) = \psi_z \{1 - e^{-K''t} [1 + K''t + 1/2(K''t)^2 + 1/6(K''t)^3 - B''(K''t)^4]\}. \quad (1)$$

In all such parameterizations, ψ_z defines the long-period source strength of the time function, K'' is inversely proportional to the rise time of the time function, and therefore controls the far-field source corner frequency, and B'' is a dimensionless parameter controlling the amount of overshoot of the RDP. The " superscripts emphasize the fact that the "*K*" and "*B*" parameters differ between the various modifications of the Haskell model, although their influence is similar in each case. Haskell (1967) proposed that, on the basis of dimensional arguments, ψ_z should scale directly with yield, that B'' should be dependent only on the source medium, and that K'' should scale inversely with the cube-root of yield.

von Seggern and Blandford (1972) presented the first detailed source models for the three Amchitka explosions. They showed that the short-period amplitude ratios (~ 1 -sec period) at seven LRSM stations and the spectral ratios (2.0- to 0.2-sec period) at RK-ON for *C/L* and *M/L* were not well-predicted by cube-root scaling of the Haskell source model. A better fit to the data was found using a modified

Haskell model of the form

$$\psi(t) = \psi_{\infty} \{1 - e^{-K't} [1 + K't - B'(K't)^2]\}. \quad (2)$$

The far-field source function for this model has a high-frequency spectral fall-off proportional to ω^{-2} , compared with ω^{-4} for the Haskell model, which was credited with improving the fit to the observations. The baselines for the parameters in (2) were established by fitting the observed RDP for the 5-kt explosion HARDHAT (Werth and Herbst, 1963), and then the Haskell yield-scaling laws for ψ_{∞} and K' were used to predict the source parameters of the Amchitka tests. These parameters are given in Table 4. The ψ_{∞} values were not explicitly constrained by absolute amplitude information and are arbitrarily set in Table 4. von Seggern and Blandford (1972) showed that the source representation given by (2) has the same spectral fall-off as the Mueller-Murphy (1971) source model. However, the corner frequency

TABLE 4
SCALING-LAW DETERMINED SOURCE MODELS*

Source Model	Event	K (sec ⁻¹)	B	ψ_{∞} (10 ¹¹ cm ³) [†]
von Seggern and Blandford with cube-root scaling of K and direct yield-scaling of ψ_{∞}	LONGSHOT	6.67	2.04	0.112
	MILROW	2.87	2.04	1.4
	CANNIKIN	1.68	2.04	7.0
von Seggern and Blandford with Mueller-Murphy scaling of K and direct yield-scaling of ψ_{∞}	LONGSHOT	9.6	2.04	0.112
	MILROW	5.2	2.04	1.4
	CANNIKIN	3.6	2.04	7.0
Haskell model with cube-root scaling of K and direct yield-scaling of ψ_{∞}	LONGSHOT	12.59	0.24	0.112
	MILROW	5.40	0.24	1.4
	CANNIKIN	3.12	0.24	7.0
Haskell model with Mueller-Murphy scaling of K and direct yield-scaling of ψ_{∞}	LONGSHOT	18.17	0.24	0.112
	MILROW	9.88	0.24	1.4
	CANNIKIN	6.79	0.24	7.0

* HARDHAT is the reference event in each case.

† Arbitrarily set to 1.4×10^{11} cm³ for MILROW.

scaling for the latter model incorporates an additional depth-dependence leading to the relation (Mueller and Murphy, 1971);

$$K' \propto h^{0.42}/W^{0.33}, \quad (3)$$

where h is the source depth. Scaling K' from HARDHAT using equation (3) for the von Seggern source gives the second set of source parameters in Table 4. Table 4 also lists the source parameters for the Haskell model [equation (1)] under the assumption of cube-root scaling of the HARDHAT results (von Seggern and Lambert, 1970; Hasegawa, 1973; Basham and Horner, 1973), as well as values of K'' found using (3).

The far-field source spectra [$\psi(t)$] for the four source models in Table 4 are compared in Figure 2. Figure 2a illustrates one of the principal failings of the direct cube-root scaling of K'' for the Haskell model, which is that it leads to greater high-frequency radiation for small yield events than for large events (von Seggern and

Lambert, 1970; Murphy, 1977). If the depth effect is included in scaling the corner frequency, this does not occur (Figure 2b). The von Seggern and Blandford (1972) parameterization does not have a similar problem, due to the different high-frequency roll-off. Note that for periods longer than 1 sec, the two source models are similar when the cube-root scaling is adopted (Figure 2, a and c), but that at higher frequencies the relative amplitudes between the events differ (von Seggern and Blandford, 1972). When the depth dependence is included in the corner frequency scaling (Figure 2, b and d), the source spectra do not begin to differ significantly until frequencies greater than 2 or 3 Hz, and for both models the high-frequency radiation is substantially greater than predicted for the cube-root scaling

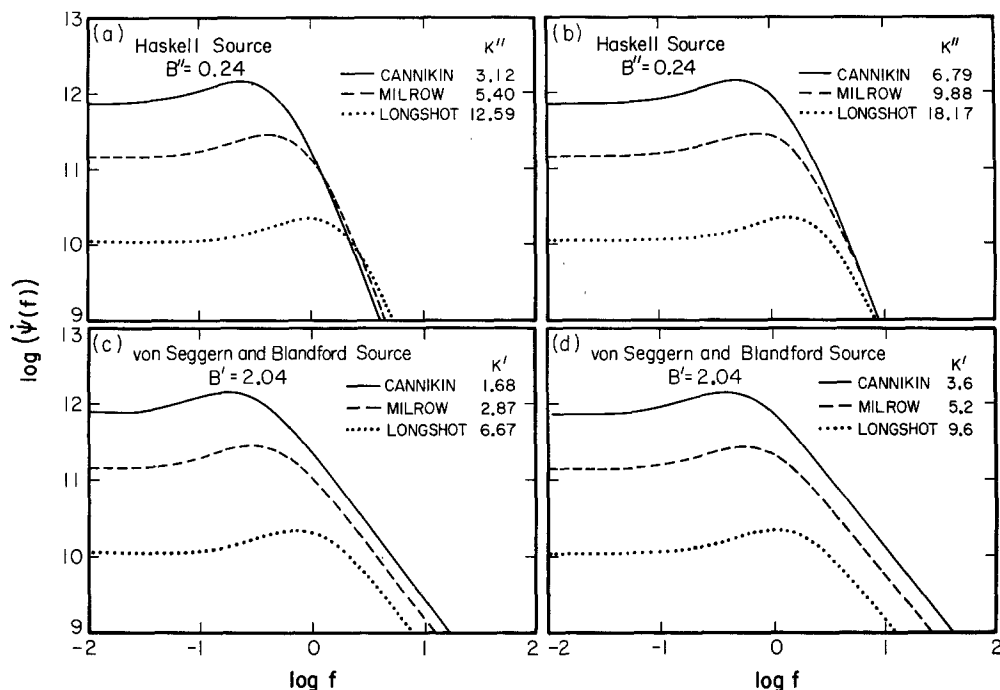


FIG. 2. Amplitude spectra of the far-field source functions predicted for the Amchitka tests using scaling relations. In all cases, HARDHAT was the reference event, and the long-period levels were scaled directly with yield. Table 4 lists the source parameters. (a) Haskell source model with cube-root scaling of K'' . (b) Haskell source model with Mueller-Murphy scaling of K'' . (c) von Seggern and Blandford source model with cube-root scaling of K' . (d) von Seggern and Blandford source model with Mueller-Murphy scaling of K' .

models. The spectra in Figure 2d are very similar to those predicted for the Mueller-Murphy model because the corner frequency is scaled by (3) and the spectral fall-off is the same. The only major difference is that the Mueller-Murphy model the long-period scaling would not be directly proportional to yield, and the amount of overshoot would increase slightly with increasing yield as a result. Murphy (1977) has summarized the evidence supporting the superiority of the Mueller-Murphy corner frequency scaling over the cube-root scaling, and provides a convincing case. There is greater uncertainty in which high-frequency roll-off is most appropriate (Rodean, 1980).

A significant advance in establishing the absolute source levels of the Amchitka tests and in providing empirical constraints on the high-frequency radiation was

made by Burdick *et al.* (1984). In that study, a second modification of the Haskell source representation was used, given by

$$\psi(t) = \psi_{\infty} \{1 - e^{-Kt} [1 + Kt + (Kt)^2/2 - B(Kt)^3]\}. \quad (4)$$

Source representations were determined by modeling strong ground motion P and Rayleigh wave velocity waveforms in the ranges 7 to 12 km from MILROW and 10 to 20 km from CANNIKIN. Source region velocity structures, K , and $B - \psi_{\infty}$ combinations (Table 5) were determined for each event. The strong motion data did not have sufficient long-period energy to constrain the amount of overshoot in the source potentials, so that unique values of B and ψ_{∞} could not be independently determined. B was assumed equal to 1 in obtaining the models in Table 5. Given the trade-offs in determining the velocity structure and the source parameters, a fairly wide range of B values could be used without degrading the fit of the synthetics to the observations. The near-field data do provide strong constraints on the absolute levels of the source spectra at high frequencies. No comparable near-field, strong motion records are available for LONGSHOT. The source representation (4) has a high-frequency spectral fall-off proportional to ω^{-3} . No difficulty was encountered in modeling the observations in the period range 2.0 to 0.3 sec using

TABLE 5
EMPIRICAL HIGH-FREQUENCY SOURCE MODELS FOR AMCHITKA*

Event	K (sec ⁻¹)	B	ψ_{∞} (10 ¹¹ cm ³)	Reference
MILROW	9.0	1	1.4	Burdick <i>et al.</i> (1984)
CANNIKIN	6.0	1	4.5	Burdick <i>et al.</i> (1984)
LONGSHOT	16.7	1	0.2	Lay <i>et al.</i> (1984a)
MILROW	9.0	1	1.4	Lay <i>et al.</i> (1984a)
CANNIKIN	6.0	1	4.0	Lay <i>et al.</i> (1984a)

* For the source representation given by equation (4).

(4), and the empirically determined values of K prove to be very consistent with the predictions of the Mueller-Murphy model [equation (3)], although it is not possible to confidently rule out simple cube root scaling of K . This again indicates that appropriate depth and yield-scaling of the source corner frequency is more important than the spectral decay, at least for frequencies less than 3 Hz.

In order to obtain a compatible high-frequency source model for LONGSHOT, Lay *et al.* (1984a) applied a relative waveform comparison technique to a large number of teleseismic WWSSN short-period P waves from the Amchitka events. Because the data were again narrow band, high-frequency signals, there was no sensitivity to B alone, and it was assumed that $B = 1$ for the analysis. The source model given by (4) was used and the MILROW model found by Burdick *et al.* (1984) was kept fixed. K for LONGSHOT was set using (3), and the values of ψ_{∞} for LONGSHOT and CANNIKIN listed in Table 5 were determined. The procedure used emphasizes the longer periods in the signals, and thus the estimates of the source strength are most reliable for periods around 1 sec. Under the assumption of constant B the resulting yield-scaling for ψ_{∞} for the Amchitka events was found to be $\psi_{\infty} \propto W^{0.73}$. While the yield exponent is close to the Mueller-Murphy model prediction of 0.76, the assumption of constant overshoot is not consistent with their model. Adopting the Mueller-Murphy variable overshoot would give a yield exponent of 0.67, which is only slightly smaller due to the slow increase in B with increasing yield, but as shown below this goes in the wrong direction for the long-period observations.

While the studies of Burdick *et al.* (1984) and Lay *et al.* (1984a) were unable (and not intended) to constrain the long-period source scaling, they do provide robust absolute source spectral estimates for the Amchitka events in the period range 0.5 to 2.0 sec. These studies also provide further confirmation of the validity of the depth-dependent scaling of the corner frequency of the Mueller-Murphy model. Figure 3 shows the far-field source spectra, $\dot{\psi}(f)$, for the events using the source parameters given by Lay *et al.* (1984a) (Table 5). The amplitude response of the WWSSN short-period instrument and the range of response of the near-field velocity meter which recorded the strong ground motion records are also shown. These spectra illustrate the lack of sensitivity of the near-field and teleseismic short-period P waves to the long-period level of the source spectrum. The portions

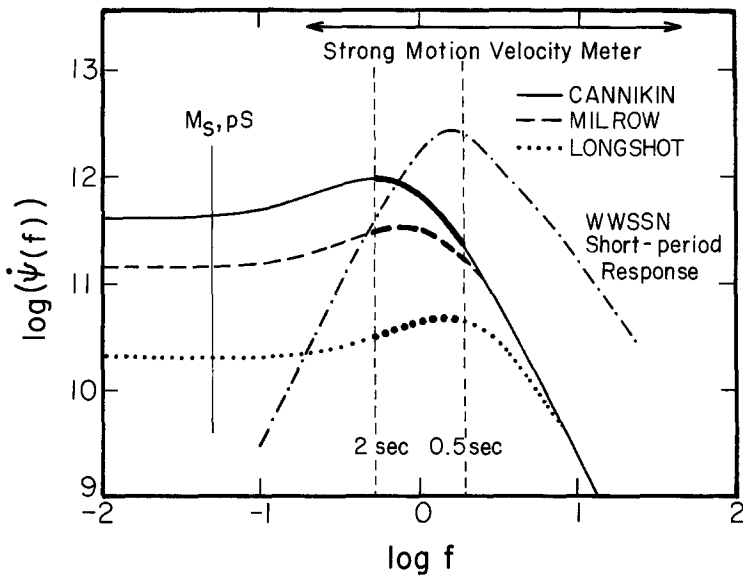


FIG. 3. Amplitude spectra of the far-field source functions for the Amchitka tests empirically constrained by high-frequency data. The source parameters are those determined by Lay *et al.* (1984a), which are listed in Table 5. The range of frequency response of the velocity meter which recorded the near-field records modeled by Burdick *et al.* (1984) is shown at the top. The amplitude response of the WWSSN short-period instrument indicates the frequency band of the data modeled by Lay *et al.* (1984a). As a result of these limitations, the source models are considered well-constrained in the period range 2 to 0.5 sec, where the spectral curves are drawn in heavy line.

of the source spectra that are considered to be well-constrained are indicated by the heavy line. Note that the 20-sec information provided by M_s or long-period pS should help to constrain the long-period spectral levels, which in turn should determine any relative variation in overshoot behavior. For reference, we note that a B value of 1 in the source representation (4) produces a factor of 1.95 overshoot of the RDP and a corresponding overshoot in the far-field source spectrum (RVP) by a factor of 2.35.

Before analyzing the long periods, it is important to consider whether the results in Figure 3 would be significantly different had an alternate source representation been used in the modeling. Figure 4 compares the far-field source spectra from Figure 3 with spectra for the von Seggern and Blandford model [equation (2)]. In order to simplify the comparison, the same ψ_∞ values were used, and the RVP overshoot was set to be the same for both models (giving $B' = 2.5$). The values of K' used in the von Seggern and Blandford model spectra were those obtained by

scaling the HARDHAT results using the Mueller-Murphy scaling of equation (3). This figure illustrates that the primary differences in the two source representations resulting from the difference in spectral fall-off are manifested at frequencies greater than 2 or 3 Hz, and the differences are not appreciable until about 5 Hz. While the von Seggern and Blandford model parameters used in Figure 4 are not necessarily the exact ones that would have been found had the modeling performed by Burdick *et al.* (1984) and Lay *et al.* (1984a) been done using (2), it is clear that the following conclusions regarding the relative scaling of short- and long-period source spectra are not strongly dependent on the high-frequency spectral roll-off.

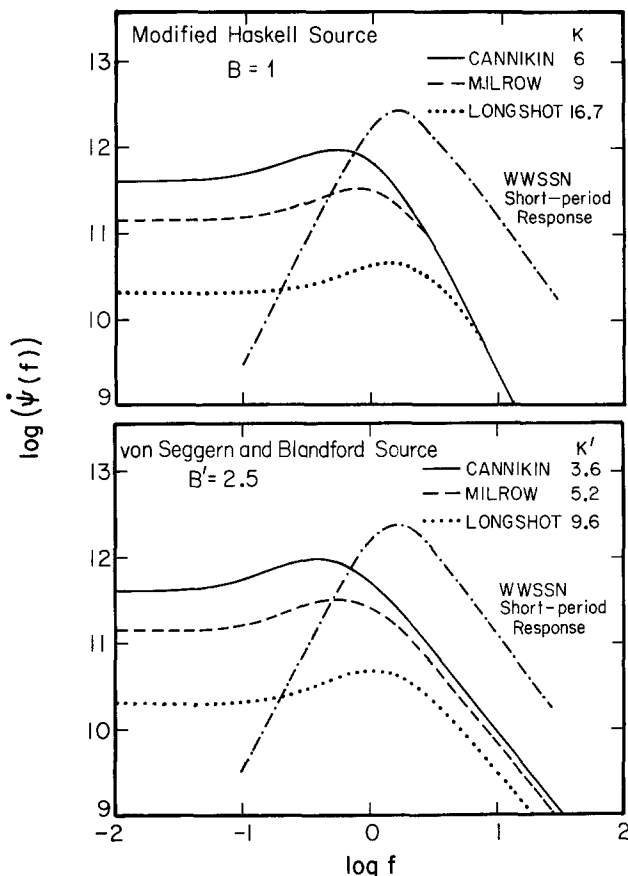


FIG. 4. Comparison of the source spectra in Figure 3, which are for the modified Haskell model of equation (4), with von Seggern and Blandford source models. The latter were constrained to have the same long-period levels and the same amount of overshoot as the former. K' was scaled from the HARDHAT results using equation (3).

Determining the absolute level of the long-period source spectrum for each event presents many difficulties. Absolute moments determined from M_s are subject to large uncertainty due to the necessity of correcting for attenuation and propagation effects on Rayleigh waves, and corresponding difficulties exist for pS arrivals. We will concentrate on finding models for which the relative source behavior is consistent with the observations, as well as being compatible with the few absolute level estimates that can be made. This baseline uncertainty is of secondary importance to establishing the broadband yield-scaling relations.

Using the source models shown in Figure 3, along with near-field determinations of the source region velocity structures (Burdick *et al.*, 1984), one can predict the relative pS and Rayleigh wave amplitudes. This is particularly straightforward for the pS phases, for which the excitation is essentially dependent only on the P -wave velocity at the source and the shallow source region crustal structure. For MILROW, the source P velocity is 4.2 km/sec, and for CANNIKIN it is 4.7 km/sec. The predicted average pS amplitude ratio $C/M \approx 3.34$. This is about 40 per cent lower than observed. A more complicated calculation, performed using the theory of Harkrider (1980), was made for the theoretical 20-sec Rayleigh wave amplitudes for all three events. Using an energy flux approximation, the source region structures, which differ slightly below the MILROW and CANNIKIN shot points (see Burdick *et al.*, 1984), were coupled with oceanic propagation paths, and Rayleigh wave synthetics were computed. This procedure reaffirmed the approximate scaling: Rayleigh wave amplitude $\propto \mu\psi_z$, for a fixed source model in a given structure (Harkrider, 1980; Bache, 1982). We also found that the differences between the MILROW and CANNIKIN source velocity structures affect the relative amplitudes by a few per cent. Since LONGSHOT was detonated closer to the MILROW shotpoint, computations for both events were done with the same structure. This results in a source velocity of 3.7 km/sec for LONGSHOT, and a rigidity ratio $L/M \sim 0.9$. After confirming that the 20-sec Rayleigh wave amplitudes were not sensitive to changes in B for fixed ψ_z , as indicated by Figure 3, the source models in Figure 3 were used to determine the predicted Rayleigh wave amplitude ratios $C/M \approx 3.0$ and $M/L \approx 7.84$. These ratios are only slightly different from the ψ_z ratios of 2.86 and 7.0, respectively. Thus, the predicted long-period amplitude ratios are not consistent with the pS and Rayleigh wave observations.

As was discussed earlier, the high-frequency modeling which produced the source parameters in Table 5 was not sensitive to changes in B alone, therefore we can change B and ψ_z to agree with the long-period constraints without having to recompute the short-period synthetics, as long as the high-frequency spectral levels are kept unchanged. We adopted this simple procedure and made several tests to ensure that the new models are in fact compatible with the short-period data. Because we do not have a very reliable constraint on the absolute long-period level of any of the Amchitka events, we chose to arbitrarily keep the MILROW model fixed, with $B = 1$. The amount of overshoot that this B implies is comparable to that for the granite model (HARDHAT) of Haskell (1967), which is considered to be reasonable for the Amchitka source material (von Seggern and Lambert, 1970; Basham and Horner, 1973). New CANNIKIN and LONGSHOT $B - \psi_z$ combinations were determined by requiring that the long-period Rayleigh wave amplitude ratios be $C/M = 4.3$ and $M/L = 11.5$. The resulting far-field source spectra are shown in Figure 5, and the initial and revised RDPs are shown in Figure 6. The source parameters for these models are given in Table 6.

One of the tests of the revised source models was to redo the relative waveform analysis of the short-period teleseismic signals using the new values of B . Following the same procedure for the intercorrelation method described by Lay *et al.* (1984a), the ψ_z estimated for LONGSHOT using MILROW as a master event was $1.42 \cdot 10^{10} \text{ cm}^3$, while with CANNIKIN as a master event the result was $1.44 \cdot 10^{10} \text{ cm}^3$. These are both within a few per cent of the value in Table 6. The CANNIKIN ψ_z estimated with MILROW as a reference event was $5.93 \cdot 10^{10} \text{ cm}^3$. The consistency of these results justifies the simple approach we adopted for estimating the source parameters.

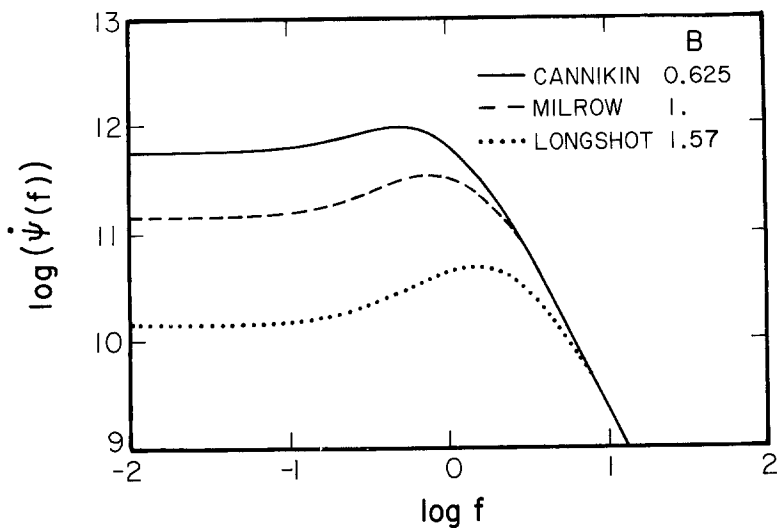


FIG. 5. Amplitude spectra of the far-field source functions for the Amchitka tests empirically constrained by broadband data. B and ψ_{∞} were adjusted from those in Figure 3 to agree with the long-period observations. The source parameters are listed in Table 6.

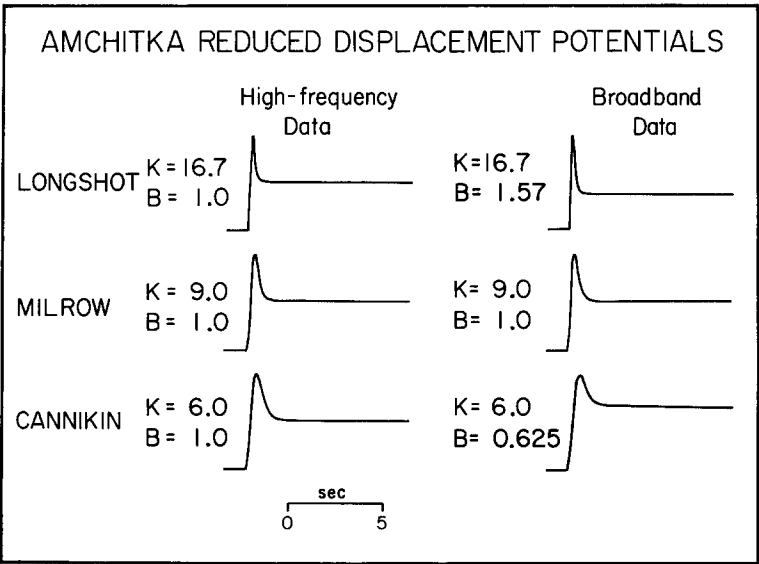


FIG. 6. Reduced displacement potentials corresponding to the source models in Figures 3 and 5 (see Tables 5 and 6). The broadband data require a decrease in overshoot with increasing yield.

TABLE 6
EMPIRICAL BROADBAND SOURCE MODELS FOR
AMCHITKA*

Event	K (sec ⁻¹)	B	ψ_{∞} (10 ¹¹ cm ³)
LONGSHOT	16.7	1.57	0.137
MILROW	9.0	1.0	1.4
CANNIKIN	6.0	0.625	5.69

By comparing Figures 5 and 3, it is clear that the changes in B produce almost no effect on the spectra in the period range 2.0 to 0.5 sec, thus the high-frequency source characteristics are unaltered. The modified models now satisfy the seismic observations in the entire period range 20 to 0.5 sec. Figures 5 and 6 show that the amount of overshoot decreases with increasing yield, and hence with increasing depth of burial. Using the parameters in Table 1 the following relations are found

$$\log \psi_{\infty} = 8.424 + 0.9019 \log W \quad (5)$$

$$\log B = 0.6248 - 0.2188 \log W \quad (6)$$

$$\log B = 0.0570 - 0.9701 \log h \quad (7)$$

$$\log O_1 = 0.3395 - 0.6238 \log h \quad (8)$$

$$\log O_2 = 0.4218 - 0.7701 \log h \quad (9)$$

where O_1 is the time domain overshoot of the explosion RDP, and O_2 is the spectral amplitude overshoot of the explosion RVP. The latter two relations are provided to relate the B values for the source representation (4) with other parameterizations.

Since the source parameters probably depend on both yield and depth, it is desirable to combine these relations. Under the assumption that $\psi_{\infty} \sim h^{-1/3}$, the following expression is obtained

$$\psi_{\infty} = 1.69 \cdot 10^8 W^{0.98} / h^{1/3}. \quad (10)$$

This is similar to the expression found by Murphy and Mueller (1971) which gives $\psi_{\infty} \sim W/h^{0.27}$ and agrees closely with the results of finite difference calculations which predict ψ_{∞} -dependent $W/h^{1/3}$ (Bache, 1982).

As mentioned above, the absolute level of ψ_{∞} , and hence of B , is uncertain for each event. However, the yield and depth dependence of these parameters is free of this baseline uncertainty. Two tests of the absolute value of ψ_{∞} for CANNIKIN were available. One stems from the seismic moment determination for the CANNIKIN explosion by Toksöz and Kehrner (1972) of $M_{0\text{exp}} \approx 5.0 \times 10^{24}$ dyne cm. Using the well-known relation

$$M_{0\text{exp}} = 4\pi\rho\alpha^2\psi_{\infty} \quad (11)$$

we obtain $\psi_{\infty} \approx 7.2 \times 10^{11} \text{ cm}^3$, which is only 27 per cent larger than the value obtained in our revised model in Table 6. The uncertainty in the orientation and moment of the tectonic release for CANNIKIN, along with the baseline uncertainties due to attenuation and structural effects, preclude using the larger number as a reliably fixed value. Had we done so, the B value for CANNIKIN would be $B \approx 0.42$, and the other sources would be modified accordingly. A second check on the absolute level for CANNIKIN is given by the average teleseismic pS amplitude at WWSSN stations (Table 1). The uncertainty in the average value of t_{c}^* appropriate for the particular paths contributing to that average pS amplitude complicates interpreting this number. Using the Lay *et al.* (1984a) parameters for CANNIKIN, an average $t_{\text{c}}^* \approx 2.25$ sec is required to produce the observed value of 2083 $m\mu$. This number is not unreasonable; however, the average t_{c}^* found for the short- and long-period P waves from Amchitka events to WWSSN stations is ~ 0.9 sec (Burdick *et*

al., 1984), thus one might expect a larger value of t_{β}^* . Using the revised values of B and ψ_z in Table 6 leads to an estimate of $t_{\beta}^* \approx 2.9$ sec, which is in better agreement with the relation $t_{\beta}^* = 4.0 t_{\alpha}^*$. A value of $B = 0.36$ for CANNIKIN would result in $t_{\beta}^* \approx 3.6$ sec. Since the frequencies involved, the number of observations, and the individual paths are not uniform in this comparison, this may be a fortuitous result. However, it does lend some credence to the possibility of low B values for CANNIKIN. Douglas *et al.* (1983) have shown that the long-period P wave modeling of Burdick and Helmburger (1979) does not unambiguously resolve large overshoot for CANNIKIN.

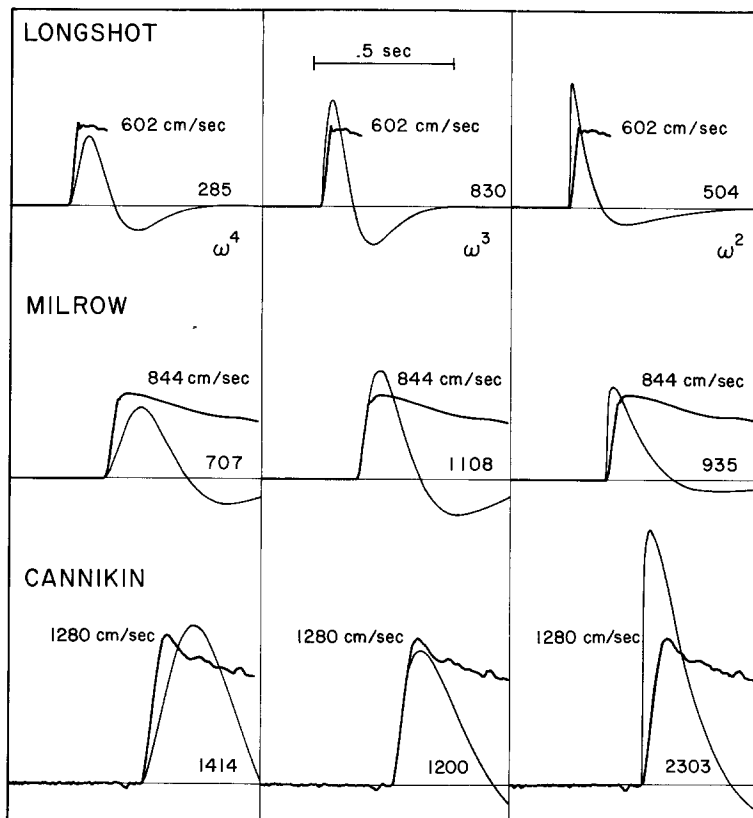


FIG. 7. Comparison of the theoretical predictions of the Haskell model and modifications (ω^4 , ω^3 , and ω^2) with strong motion observations (vertical velocity).

One final check on the compatibility of the various source parameterizations is to examine the rise-time predictions at up-hole distances. The corresponding vertical motions observed at the three test sites are displayed in Figure 7. There are numerous surface measurements for these events with amplitudes quite compatible with those given in Figure 7. Thus, we have no reason for their rejection although they are, indeed, very strong motions, see Perret (1972a, b). Note that the observed velocities do not fall-off with time because of spall while any elastic calculation must, as indicated by the theoretical predictions. The elastic model used in these calculations is that of Burdick *et al.* (1984) with the source parameter specified in Tables 4 and 6. We used the Mueller-Murphy scaling set of values throughout since they gave the most promising results. Note that the rise-time for the (ω^2) model is

nearly zero since the analytical derivative of expression (2) is singular. Numerically, the slope is limited by the time spacing of the Green's functions ($\delta t = 0.005$ secs) which was the same for all three events. Thus, the relative peak amplitudes are still meaningful in that the high frequencies (short-periods) remain well separated for all yields. The rise-time for the (ω^4) model is too long for all three events. On the other hand, the success of the (ω^3) model is remarkable and, obviously, not well understood since the strain rates implied for CANNIKIN are huge. Perhaps, rocks are much stronger under pure compression than generally appreciated. At any rate, the (ω^3) model would appear to be the most appropriate parameterization for this type of data.

DISCUSSION

The previous analysis showed that in order to explain the broadband seismic observations in the period range 20 to 0.5 sec, the explosion source functions for the Amchitka tests must have decreasing overshoot with increasing yield. The Mueller-Murphy model predicts an increase in overshoot with yield. This is largely a consequence of the ψ_z scaling adopted for their model, which incorporates an empirical depth dependence of the cavity radius, r_c

$$r_c \propto W^{0.29} h^{-0.11} \quad (12)$$

(Mueller and Murphy, 1971). For an incompressible material model, it can be shown that (Mueller and Murphy, 1971)

$$\psi_z = r_c^3/3. \quad (13)$$

Allowing for a cube root of yield dependence on burial depth, this leads to the relation (Murphy, 1977)

$$\psi_z \propto W^{0.87} h^{-0.33} \sim W^{0.76}. \quad (14)$$

Given the relatively weak depth dependence of surface wave excitation for explosions (Tsai and Aki, 1971; Cherry *et al.*, 1974; Harkrider, 1980) this indicates that

$$M_s \propto 0.8 \log W. \quad (15)$$

However, the observed $M_s - \log W$ slope is close to unity for Amchitka and other test sites. Murphy (1977) attributes the observed slope as being increased due to the effects of slapdown. Finite difference calculations predict a yield scaling relation of

$$\psi_z \simeq Wh^{-0.33} \sim W^{0.89} \quad (16)$$

(Bache, 1982). Allowing for the depth dependence of surface wave excitation, these models predict M_s scaling with a slope slightly greater than 0.9. The dimensional arguments of Haskell (1967) predict a linear relation between ψ_z and yield. Equations (5) and (10) are very similar to the yield-scaling predicted by numerical calculations, indicating that the long-period scaling of the Mueller-Murphy model is not accurate in this case. The generality of this result is indicated by the M_s -yield behavior observed in other regions. Allowing for near-linear scaling between

ψ_x and yield accounts for the $m_b - \psi_x$ observations compiled by Murphy (1974, 1977), the M_s scaling with yield, and the linearity of $m_b - M_s$ relations (Springer and Hannon, 1973). One explanation is that neglecting material properties as a function of depth and inaccuracy of the physical model leading to (13) are responsible for this breakdown of the Mueller-Murphy long-period yield-scaling. Rather than using the actual cavity radius to scale ψ_x , one should adopt an "equivalent" cavity radius that accounts for the explosion nonlinearities. This "equivalent" radius is bounded by the cavity radius and the elastic radius (Day *et al.*, 1983a). Slapdown does not appear to be a significant source of long-period radiation (Day *et al.*, 1983b), and the agreement in long-period amplitude ratios from M_s and pS observations would be difficult to account for by slapdown effects.

Some finite difference models predict decreasing overshoot with increasing depth of burial; the result of increasing shear strength with increasing overburden pressure (Rodean, 1971). Equation (7) indicates that the Amchitka data support this prediction. The effect on the explosion RDPs is shown in Figure 6, where the amount of overshoot decreases by almost a factor of 2 between LONGSHOT and CANNIKIN. A clear empirical documentation of this effect has not been presented in the literature previously. While it is reasonable to expect that the amount of overshoot is not directly dependent on yield, and that it is the depth effect that influences it, it may be either the depth dependence of the overburden pressure, of the material properties, or of the variation in emplacement medium that produces the Amchitka behavior. LONGSHOT was detonated in an andesite-basalt layer, while MILROW and CANNIKIN were in pillow lava layers (Perret, 1972a; King *et al.*, 1974), which may have some high-frequency coupling effect. The limited number of events precludes more detailed investigation of this question.

Lay *et al.* (1984a) discuss a problem in reconciling the results of forward modeling of the short-period P waves for the Amchitka tests and the results of the relative waveform and scaling-law analyses. The essence of the problem is that the short-period P waves from LONGSHOT are somewhat larger than predicted, even though the 1-sec spectral levels are compatible with the scaling law predictions. It is difficult to account for this observation by frequency-dependent attenuation or other path properties, nor can the corner frequency scaling or high-frequency spectral roll-off of the different source parameterizations account for the anomaly. One possibility is that for the high-frequency, low yield event LONGSHOT, the rate of spectral fall-off is less rapid than for the larger events. This would require a more complicated source parameterization than adopted in any analysis to date, and there is no evidence of this in the very near-in velocity records in Figure 7. Very broadband data is required to explore such a possibility for future events. With this exception, the source models presented in Figures 5 and 6 are compatible with the complete range of seismic observations available for the Amchitka tests.

As a preliminary investigation of the broadband yield-scaling behavior for other test sites, we made short- and long-period measurements for several Pahute Mesa events. The short-period measurements were the first peak-to-first trough amplitudes at all available WWSSN and CSN stations. Relative event size amplitude factors were then determined, as discussed by Lay *et al.* (1984b). The long-period measurements were made for the pS and Rayleigh wave amplitudes at OXF for each event. Care was taken in measuring the same portion of the waveforms for each event. We found that the pS amplitudes are linearly related to the Rayleigh wave amplitudes with very little scatter. OXF is at an azimuth of 90° from NTS, which is close to the expected SV and Rayleigh wave tectonic release radiation node

for the nearly north-south trending vertical strike-slip tectonic release orientation characteristic of Pahute Mesa events. Figure 8 shows the ratios of the average short-period P -wave amplitude divided by the long-period OXF pS amplitude for each event as a function of source depth. There is a clear tendency for deeper events to have lower ratios, which is the trend expected if overshoot decreases with increasing burial depth. The curve connects the observed (predicted for LONGSHOT) ratios for the Amchitka data plotted with an arbitrary baseline.

Qualitatively, it appears that the Pahute Mesa and Amchitka data may have a similar depth dependence of relative high- and low-frequency yield-scaling. However, much work will be necessary to prove whether or not this is the case. Several of the events with the lowest amplitude ratios, particularly BENHAM and MUENSTER, are known to have significant tectonic release, and the long-period amplitudes may be increased as a result. There is a correlation between M_s and SH

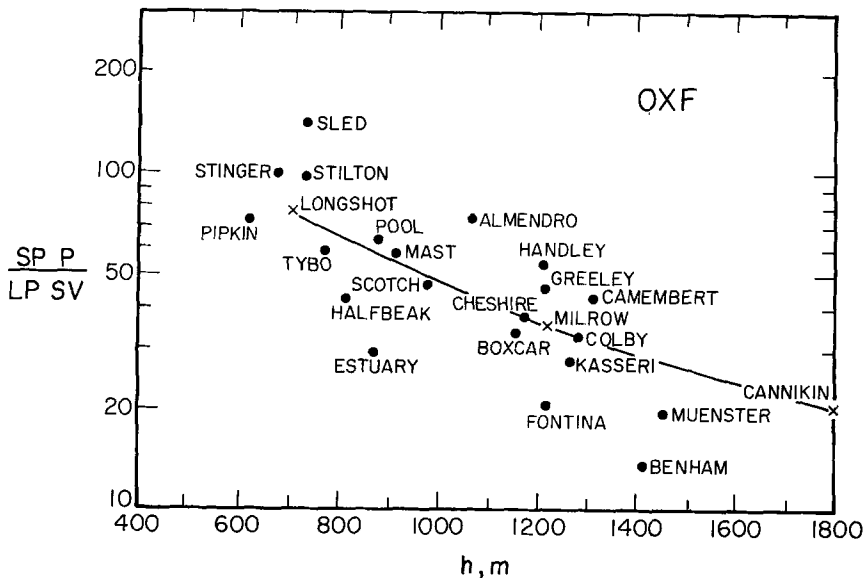


FIG. 8. The ratios of (globally averaged short-period P -wave "b" amplitudes)/(long-period pS amplitudes recorded at OXF) for Pahute Mesa events are plotted as a function of source depth. Comparable ratios are plotted for the Amchitka events with an arbitrary baseline, and these are connected by the curve.

amplitudes at OXF for these events also, although the scatter is much greater than for SV and M_s . It is possible that contamination from tectonic release produces the trend in Figure 8, particularly if the relative amount of tectonic release increases with source depth. However, the F factor is much larger for GREELEY than for HANDLEY, KASSERI, or FONTINA (Lay *et al.*, 1984b), yet GREELEY does not have an anomalously low ratio, thus it is not reasonable to summarily dismiss the trend in Figure 8 as due to tectonic release. Aki *et al.* (1974) have argued for large overshoots for several small yield Yucca Flats events, but larger events have not been studied in corresponding detail. Further detailed study of broadband data will provide the answers to the important questions of short- and long-period yield-scaling and the nature of overshoot.

The modified Haskell source models adopted for this study prove sufficient for modeling the seismic data available in the near- and far-field in the period range

20.0 to 0.5 sec. The appropriateness of these source representations at longer periods is open to some question. Many studies have suggested that the long-period source spectrum continues to drop-off with increasing period (Toksöz *et al.*, 1964; Molnar *et al.*, 1969; Savino *et al.*, 1971; Helmberger and Harkrider, 1972). While many of these observations can be explained by the source-depth effects (Tsai and Aki, 1971), there remains some uncertainty in the nature of explosion moments, as discussed by Müller (1973) and Rodean (1980). Future efforts should emphasize broadband data spanning at least the period range 20 to 0.2 sec if appropriate scaling laws are to be established for parametric source function representations.

CONCLUSIONS

An investigation of broadband seismic data for the three underground nuclear explosions at the Amchitka test site provides empirical yield-scaling behavior in the period range 0.2 to 20 sec. The source corner frequency scales in accordance with the Mueller-Murphy law which predicts $K \propto h^{0.42}/W^{1/3}$, where h is the source depth, W is the yield and K is the parameter controlling the corner frequency in the Haskell-type source representations. The long-period levels scale with $W^{0.9}$, in agreement with finite difference calculations. Overshoot of the source function decreases with increasing source depth for the Amchitka events, which is predicted by some finite difference models, but not by the Mueller-Murphy model. A preliminary investigation of seismic data for Pahute Mesa events indicates that similar source scaling applies for that test site, although the effects of tectonic release on long-period radiation must be accounted for by future detailed analysis. The simple form of the yield-scaling relations for the parameters in the explosion source functions used should facilitate accurate yield estimation.

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